

## WANDERING BLACK HOLES IN BRIGHT DISK GALAXY HALOS

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## ABSTRACT

We perform SPH+N-body cosmological simulations of massive disk galaxies, including a formalism for black hole seed formation and growth, and find that satellite galaxies containing supermassive black hole seeds are often stripped as they merge with the primary galaxy. These events naturally create a population of “wandering” black holes that are the remnants of stripped satellite cores; galaxies like the Milky Way may host 5 – 15 of these objects within their halos. The satellites that harbor black hole seeds are comparable to Local Group dwarf galaxies such as the Small and Large Magellanic Clouds; these galaxies are promising candidates to host nearby intermediate mass black holes. Provided that these wandering black holes retain a gaseous accretion disk from their host dwarf galaxy, they give a physical explanation for the origin and observed properties of some recently discovered off-nuclear ultraluminous X-ray sources such as HLX-1.

*Subject headings:* galaxies : formation — galaxies : evolution — galaxies : halos — black hole physics

## 1. INTRODUCTION

Recent evidence for the existence of intermediate mass black holes (IMBHs) raises questions about how such objects might form and evolve. IMBH candidates exist in globular clusters (Ulvestad et al. 2007), nearby bulgeless galaxies (Filippenko & Ho 2003; Barth et al. 2004), and active galactic nuclei (Greene & Ho 2004). Additionally, off-nuclear ultraluminous X-ray sources (ULXs) have become increasingly promising IMBH candidates (Farrell et al. 2009; Jonker et al. 2010). A source of IMBHs may be the seeds of supermassive black holes (SMBHs) formed at high redshift; any seed that does not grow into a SMBH would today be observed as an IMBH. While the precise mechanism for seed black hole (BH) formation is unknown, there are several postulated theories. One possible mechanism for SMBH seed formation is the direct collapse of pristine, low angular momentum gas, which forms BHs with mass on the order of  $10^4 - 10^6 M_\odot$  (Koushiappas et al. 2004; Lodato & Natarajan 2006; Begelman et al. 2006). Another possibility is that the seeds are the remnants of Population III stars, with masses around  $10^2 - 10^3 M_\odot$  (Madau & Rees 2001; Volonteri et al. 2003). Alternatively, the first nuclear star clusters may collapse to form BHs of mass 1000–2000  $M_\odot$  (Devecchi & Volonteri 2009).

We perform SPH+N-body simulations of massive disk galaxies to explore the evolution of seed BHs in a cosmological context. While previous works have addressed the growth of central SMBHs (Di Matteo et al. 2008; Okamoto et al. 2008; Booth & Schaye 2009), here we specifically focus on those which do not end up in galaxy centers. We include BH growth by gas accretion and merging, as well as radiative feedback in order to form

a fully self-consistent picture of BH growth and evolution. We find that the tidal stripping of galaxies containing SMBH seeds leads to a population of “wandering” BHs within the larger galaxy halo. Such a phenomenon has been predicted in the case of idealized simulations of merging galaxies (Governato et al. 1994; Kazantzidis et al. 2005), though fully cosmological simulations in the current  $\Lambda$ CDM paradigm are needed to test a suite of non-idealized scenarios. Wandering BHs may also be created by a gravitational slingshot from 3-body black hole interactions (Volonteri & Perna 2005), gravitational recoil, or a distribution of Population III star remnants which have not spiralled into the central BH (Schneider et al. 2002). In each of these cases, the timescale for dynamical friction is longer than a Hubble time (Taffoni et al. 2003), leaving a potentially substantial population of “wandering” IMBHs in galaxy halos.

The recent discovery of an off-nuclear IMBH candidate (Farrell et al. 2009) leads us to explore whether such an object can be explained by a “wandering” BH. The object HLX-1 is offset from the nucleus of its host spiral galaxy, and exhibits an X-ray luminosity of  $10^{42}$  ergs  $s^{-1}$ . This luminosity implies a lower limit to a black hole (BH) mass of 500  $M_\odot$ , but the true mass may be much larger. We discuss under what circumstances HLX-1 would be observable. Preliminary results suggest that HLX-1 cannot be described by an isolated wandering BH, but a BH traveling with the remnant core of its parent galaxy may explain its observed properties.

## 2. SIMULATIONS

We use the N-body code GASOLINE (Wadsley et al. 2004; Stadel 2001), an SPH tree code which incorporates star formation, gas cooling and hydrodynamics, and supernova feedback, and successfully models realistic galaxies. Studies of cosmological simulations with GASOLINE have produced galaxies that follow the mass-metallicity relation (Brooks et al. 2007) and the HI Tully-Fisher relation (Governato et al. 2009), exhibit cold flow gas accretion (Brooks et al. 2009), and reproduce the distribution of Damped Lyman Alpha systems at high redshift

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TABLE 1  
SIMULATION PROPERTIES

Run	# within $R_{vir}$	$M_{vir}$ ( $M_{\odot}$ )	$V_{circ}$ (km/s)	$R_{vir}$ (kpc)	$r_s$ (kpc)
h239	7408639	$8.32 \times 10^{11}$	247.7	242.9	2.82
h258	7347383	$7.90 \times 10^{11}$	225.4	238.8	3.81
h277	6624914	$7.09 \times 10^{11}$	262.7	230.3	2.74
h285	7373714	$8.18 \times 10^{11}$	238.2	241.5	2.24

(Pontzen et al. 2008). Additionally, Governato et al. (2010) have shown how high resolution and physically motivated supernova feedback allow for the formation of a bulgeless dwarf galaxy with a dark matter core. The ability to form realistic disk galaxies is critical to our analysis of BH physics, because of the need to accurately trace the angular momentum of inspiraling gas which comprises the disk and eventually fuels the BH, as well as the star formation histories responsible for dispensing metals into the ISM via supernova feedback.

For this Letter, we have simulated four different Milky Way-mass halos, which were selected from a uniform, 50 Mpc volume and resimulated at a high resolution using the volume renormalization technique (Katz & White 1993). All simulations are run with gravitational softening  $\epsilon = 0.3$  kpc, gas particle masses of  $2.28 \times 10^5 M_{\odot}$ , dark matter particle masses of  $1.26 \times 10^5 M_{\odot}$ , a Chabrier initial mass function (Chabrier 2003), and a *WMAP* year 3 cosmology (Spergel et al. 2007). Star formation and supernova recipes are described in detail in Stinson et al. (2006) and Governato et al. (2007); we adopt parameter values  $c = 0.1$  and  $eSN = 1.0$ . Stars are allowed to form when gas reaches a threshold density of  $1.0 \text{ amu cm}^{-3}$ , which allows us the most physical representation of star formation given our resolution. While our dwarf galaxy satellites are not resolved to the level of Governato et al. (2010), for our purposes here this resolution is sufficient. Simulation properties are described in Table 1. Circular velocity  $V_{circ}$  is measured using the width at 20% of the peak of the simulated HI line profile (see Governato et al. 2009). The disk scale length  $r_s$  is determined by simultaneously fitting an exponential + Sersic profile to the projected edge-on stellar surface density of the galactic disk.

There is much uncertainty regarding the formation of the initial “seed” black holes which grow to become SMBHs; however, they must form early on and grow quickly in order to form  $z \sim 6$  quasars (Fan et al. 2001). We maintain a physically motivated scenario by assuming seed black holes form via the direct collapse of extremely low metallicity gas as in Begelman et al. (2006). However, our choice of seed formation scenario is not crucial. We focus here on the dynamical evolution of seed BHs, which will be the same regardless of where we set the initial mass (i.e.  $100 M_{\odot}$  for the first stars or  $10^5 M_{\odot}$  for direct collapse). The dynamical friction timescale is longer than the Hubble time even for these relatively heavy seeds, given the local densities involved here. Seeds are allowed to form if the parent gas particle meets the criteria for star formation (see Stinson et al. 2006) and additionally has zero metallicity. We designate a probability that a newly formed star will instead be-

come a seed black hole with mass  $M_{BH} = 2.28 \times 10^5 M_{\odot}$ . This probability is set to 0.10 in order to reproduce the predicted black hole seed halo occupation probability at  $z = 3$  (Volonteri et al. 2008). Allowing seed BHs to form out of only pristine gas results in the truncation of seed BH formation at a redshift of  $\sim 3.5$  due to the efficient diffusion of metals produced by the first supernovae into the ISM. This criterion causes seed BHs to form in the regions of early bursts of star formation, which are primarily the centers of the first massive halos to form in the simulation. In the event that more than one BH forms at the same time within a softening length, the BHs are merged into a single BH particle, with  $M_{BH}$  as the total of the individual masses. However, we make no assumptions regarding the large-scale properties of the host halo, allowing the BHs to form based only on the properties of the local environment. BHs are not fixed at their halo centers, but are allowed to move as the forces upon them dictate. We minimize the effects of two-body interactions by adopting dark matter particle masses that are similar to gas particle masses in the high resolution region, which greatly helps the central BHs stay at their halo centers.

Black holes are presumed to accrete gas isotropically, following the formula for Bondi–Hoyle accretion. The accretion rate is limited by the Eddington rate, assuming a 10% radiative efficiency. In addition, a fraction of the rest mass energy of the accreted gas is converted to radiative energy, which is then isotropically imparted onto the surrounding gas (Di Matteo et al. 2005). To dissipate the feedback energy in a realistic way, we use a blast-wave feedback approach similar to the supernova feedback recipe described in Stinson et al. (2006). We set the fraction of radiated energy given to the surrounding gas to be 0.1%.

Black holes are allowed to merge if they (a) are within one another’s softening length and (b) fulfill the criterion  $\frac{1}{2}\Delta\vec{v}^2 < \Delta\vec{a} \cdot \Delta\vec{r}$ , where  $\Delta\vec{v}$  and  $\Delta\vec{a}$  are the differences in velocity and acceleration of the two BHs, and  $\Delta\vec{r}$  is the distance between them.

We identify galaxies and their halos with AHF (Knebe et al. 2001; Gill et al. 2004), which identifies a virial radius based on the overdensity criterion for a flat universe (Gross 1997). For each output, we identify every halo and all of the particles it contains; thus, we can track a BH’s halo residency at each timestep. We use this process to define whether a black hole is stripped from its parent halo to reside in another. A BH is denoted as “stripped” if its parent halo overdensity can no longer be detected as a separate halo. The BH is then identified as a resident of the larger galaxy, most likely in the outer regions.

### 3. RESULTS

We provide a dynamical mechanism to place massive BHs in galaxy halos, which is simply a consequence of hierarchical merging in the  $\Lambda$ CDM paradigm. Detecting these objects may help constrain the mechanism of seed BH formation, and we investigate a few scenarios in which a wandering BH may be observed as a ULX.

#### 3.1. Wandering Black Holes

For our four simulated halos, we show the radial distribution of BHs at  $z = 0$ , defined as the distance between

the halo center and the BH, in Figure 1. Each of the four galaxies has a central BH and between 5 and 15 “wandering” BHs whose distances range from 10 - 100 kpc. The vast majority of wandering BHs have grown in mass by less than 2% since their formation. A small number (5 out of 36 total) have undergone BH—BH mergers early in their lifetimes and thus have larger masses, but only one of these has experienced any substantial accretion events. In all cases accretion is effectively quenched when the host galaxies are torn apart and the BHs are left to wander throughout the halo, and thus any BHs present here are at or within a few factors of their original seed mass.

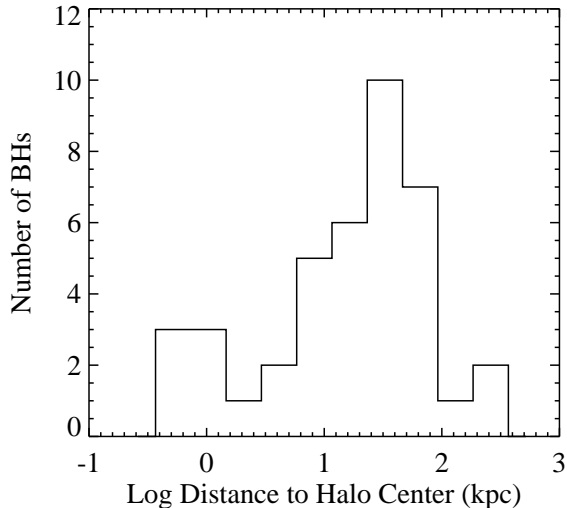


FIG. 1.— *Top Panel:* Distribution of black hole radial distances to their halo centers for 40 black holes in four simulated galaxies.

Local Group dwarf galaxies are promising targets for IMBH searches (Van Wassenhove et al. 2010). In Figure 2 we show the masses of BH-hosting satellite galaxies before the stripping process has begun. This distribution peaks between  $10^9 - 10^{10} M_\odot$ ; at halo masses of  $3 \times 10^8 M_\odot$  the satellites become increasingly dark. Since very few stars form in these halos, it is unlikely that we are underestimating the number hosting massive BH seeds, given our scenario. We estimate the absolute magnitudes of the satellites in these mass ranges using the STARBURST99 (Leitherer et al. 1999) code, using stellar ages and metallicities from our simulations. This mass range corresponds to galaxies with magnitudes fainter than -15 in the *V* band, which includes several Local Group dwarfs, including the Large and Small Magellanic Clouds. Examining these local dwarfs for IMBHs may help constrain the locations and masses of SMBH seeds. A confirmed detection of an IMBH would provide an upper limit to the initial mass of SMBH seeds and possibly allow us to differentiate between the various proposed formation mechanisms of such seeds.

### 3.2. Connection with Off-Nuclear ULXs?

While wandering BHs may be present in the Milky Way halo, observing such objects would require either a fortuitous gravitational lensing detection, or a triggered accretion event, resulting in X-ray emission. We investigate situations where a wandering BH could undergo

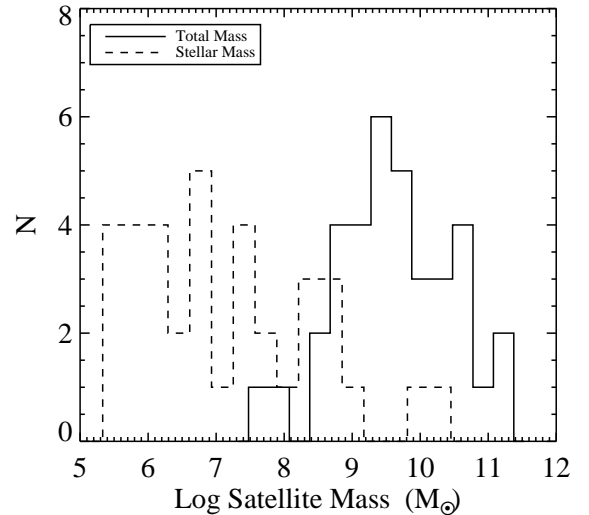


FIG. 2.— The mass distribution of BH-hosting satellites before they are stripped by the primary. The solid line indicates the total mass of the satellites, while the dashed line is the stellar mass only. Our simulations are incomplete for halos below a total mass of  $3 \times 10^8 M_\odot$ , however due to the UV background field (Haardt & Madau 1996) most halos with mass below  $10^8 M_\odot$  have very few stars.

substantial accretion in a galactic halo, which could explain the existence of objects such as HLX-1.

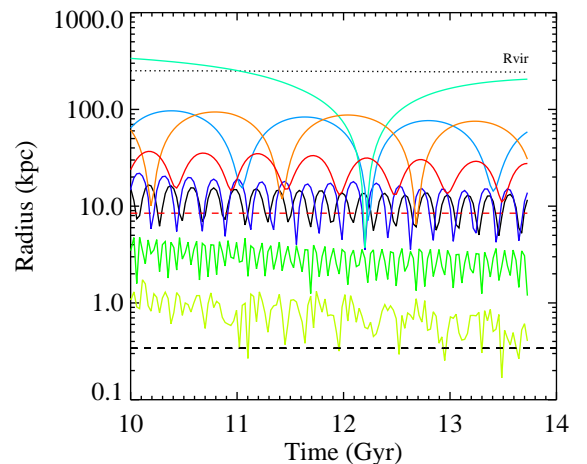


FIG. 3.— Each curve represents the radial distance vs. time of a black hole to the halo center for the simulated galaxy h239. The red dashed horizontal line denotes a distance of three scale lengths ( $r_s = 2.8$  kpc) from the center; each instance of an orbit crossing this line is defined as a disk passage. The black dashed horizontal line shows the gravitational softening, while the dotted line represents the virial radius. The yellow line indicates the central BH, while the green line denotes an inspiraling BH which has not yet reached the halo center. The other curves represent BHs which reside predominantly in the halo.

While the majority of ULXs are attributed to star formation regions (Swartz et al. 2004), a smaller number of off-planar ULXs are not cospatial with star formation, and we focus on the possible origins of these objects here. We first examine whether a wandering BH passing through a dense portion of the host galaxy disk could reproduce the properties of off-nuclear ULXs. We trace the orbits of each BH and examine the frequency with which

they cross the disk region, which we define as three disk scale lengths ( $r_s$ ). The last few Gyr of orbital history for the BHs in our simulated galaxy h239 are shown in Figure 3. Several of the BHs pass through the  $3r_s$  limit, which we denote as a disk passage. The average BH disk passage rate for all of the simulations combined is 10.6 per Gyr; however, this rate increases with time (13.3 per Gyr for the last few billion years of galaxy evolution) due to the increased population of wandering BHs in the halo (since more mergers have occurred).

The likelihood of observing such a disk passage depends on the column density of gas in the disk, the number of passages made, and the velocity of the BHs. We use results from HI measurements of the surface densities of local disk galaxies (Leroy et al. 2008) to estimate an average disk column density of  $10 \text{ M}_\odot \text{ pc}^{-2}$ . The ability of the passing BH to attract a sufficient amount of gas to be observed as a ULX depends most strongly on its velocity, which ranges between  $154 - 662 \text{ km s}^{-1}$ , and on average is  $\sim 470 \text{ km s}^{-1}$  for BHs at pericenter. To estimate a BH’s luminosity, we developed a simple scenario where the passing BH is able to collect the gas within a radius of influence determined by its mass and pericenter velocity:  $M_{\text{coll}} = \Sigma_{\text{disk}} \pi (GM_{\text{BH}}/v_{\text{BH}}^2)^2$ . We perform a Monte Carlo simulation taking into account the observed ranges of BH velocities, and estimate that the amount of mass collected by a BH during its disk passage ranges from  $10^{-3} - 10^{-4} \text{ M}_\odot$ . Assuming an accretion luminosity  $L \sim \eta \dot{M} c^2$  with  $\eta = 0.1$  and the canonical luminosity of  $L_{\text{ULX}} = 10^{39} \text{ ergs s}^{-1}$ , the BH will accrete and radiate in a high state for a mean duration of 2000 years, though a slower BH may radiate for up to  $10^5$  years. However, if the ULX transitions from a high state to a low state at any point, the accretion rate would drastically decrease and the observed emission could continue for much longer.

This simple scenario, however, is not sufficient to reproduce the properties of HLX-1, which is at least 1 kpc away from the plane of its host galaxy. A BH passing through the disk moving at a few hundred  $\text{km s}^{-1}$  will only travel a distance of  $\sim$  tens of parsecs during the duration of the predicted accretion event. Such an event would appear to be a disk ULX source, possibly indistinguishable from those cospatial with star formation regions. HLX-1 is also 1000 times more luminous and 100 times less massive (Wiersema et al. 2010., in prep.) than the assumed values in our calculation above. Taking all of these factors into account, it is unlikely that an isolated wandering BH passing through a galaxy disk can reproduce the properties of off-nuclear ULXs.

However, our wandering BH scenario would be feasible if HLX-1 is not an isolated BH, but is traveling with a bound clump of gas and stars. The magnitude and colors of the detected optical counterpart of HLX-1 are consistent with a globular cluster (Soria et al. 2009). This cluster may in fact be the stellar remnants of a stripped dwarf galaxy core that is still bound to the BH. HLX-1 could be similar to the object G1 in M31, a globular cluster that may actually be the nucleus of a stripped dwarf galaxy (Meylan et al. 2001) and harbors the most promising Local Group candidate for an IMBH (Ulvestad et al. 2007). If we presume that the wandering BHs in our simulations retain a nuclear star cluster and gas reservoir from their

parent halos, then the instance of a wandering BH passing near the center of the primary could cause instabilities in its accretion disk, triggering an accretion event of sufficient magnitude to power a ULX with a high luminosity as seen in HLX-1. Our simulations do not have sufficient resolution to follow the tidally stripped cores of galaxies in detail, though other simulations have shown that a tidally stripped dwarf galaxy can retain its core after a close passage with the primary (Mayer & Wadsley 2004). Thus, in the likely instance that a wandering BH retains the core of its host galaxy, its passage near the galaxy disk can explain the origin and properties of HLX-1.

Previous studies have estimated luminosities for massive BHs wandering through the ISM, but prior to this Letter none have explored the issue in a cosmological context. Krolik (2004) showed that IMBHs with masses ranging from  $10^2 - 10^4 \text{ M}_\odot$  can produce luminosities of ULXs if they pass through or near molecular clouds. SMBH gravitational recoil events passing through the disk may exhibit X-ray emission of  $L > 10^{39} \text{ ergs s}^{-1}$  (Fujita 2009). Mapelli et al. (2008) performed an N-body+SPH simulation of IMBHs in a galaxy merger, and found that a few halo IMBHs reside in orbits that pass through the disk, which in our scenario may be observable as ULXs.

#### 4. SUMMARY

We provide compelling dynamical scenario for the presence of “wandering” massive BHs in the halos of galaxies. A natural consequence of the hierarchical build up of galaxies in a  $\Lambda$ CDM scenario, the tidal stripping of galaxies containing seed BHs can populate the halo of a massive disk galaxy with wandering BHs. These objects often retain their original seed mass, are found throughout the galaxy halo, and may pass through the galactic disk at an average rate of  $10.6 \text{ Gyr}^{-1}$ . We predict that Local Group dwarf galaxies such as the Magellanic Clouds are likely to host IMBHs. Detections of these wandering BHs may give an upper limit to the initial mass of BH seeds, and may allow us to differentiate between the various proposed formation mechanisms of such seeds. Our scenario provides a physically motivated explanation for off-nuclear ULXs as IMBHs which have been stripped from their host galaxies, if they retain a gas reservoir/accretion disk that, when dynamically destabilized, might be funneled toward the black hole and form an accretion disk.

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